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**ESTIMATING OPTICAL IMAGING SYSTEM PERFORMANCE
FOR SPACE APPLICATIONS**

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INTRODUCTION

The photographic camera, because of its long history, is probably the best understood, and perhaps the most useful, reconnaissance device available. In more recent times the television system, an all electronic analogue of the film camera, has been developed and the spectral range of both systems has been extended to include color, near UV, and IR images. The imagery collected by these systems is readily understandable in a gross sense even by the layman and a skilled photo-interpreter is able to extract a surprising amount of information from a photographic or television image.

For many satellite applications, television systems are preferred to standard photographic methods because of the difficulty in handling and processing film aboard a spacecraft. In addition, some types of aerial film have a rather limited life in Earth orbit because of radiation sensitivity. While none of the TV techniques presently available approach the best photographic systems in overall performance primarily because of format size limitations, the state of the art has been improving rapidly in recent years and TV systems are now adequate for many applications.

Regardless of the type of optical imaging system employed, however, there are many considerations that affect their performance. Such diverse factors as scene contrast or the nature of the ground based image reconstruction equipment may have significant impact on overall performance. Therefore, a completely misleading notion of performance capabilities may be obtained by considering only the camera characteristics without taking into account the many other system elements involved.

Frequently, imaging system capabilities must be analyzed in a preliminary fashion to determine the feasibility of future space mission applications and, while detailed design considerations are clearly beyond the scope of such a feasibility analysis, the critical system elements must be adequately understood and treated to avoid gross misjudgement. This paper attempts to identify the critical system elements and provide an approach suitable for an initial

assessment of system performance. In this assessment, no attempt is made to optimize the imaging system because generally detailed constraints such as available volume, field of view, imaging system/supporting system weight trades, etc., are not known when early feasibility studies are conducted. An optimized system can only be defined when all of these constraints are defined.

The report consists of six sections. In the next section, a generalized imaging system is defined and discussed. Then, system analysis considerations are presented followed by a section on component analysis. An example of the use of this material is given next and the last section presents concluding remarks based on the report.

SYSTEM DISCUSSION

A generalized description of a spaceborne imaging system application includes the scene to be imaged, a light transmission path, a lens, a detector, relative detector-scene motion, readout, data transmission and ground reconstruction equipment as shown in Figure 1. The scene consists of an area circumscribed by the field of view (FOV) of the imaging system. Its composition, e.g., texture, relief, color, etc., and the lighting intensity and angle of incidence determine the scene contrast range and average brightness at ground level. The atmosphere, if any, scatters and absorbs some of the reflected light causing degradation in the contrast and sharpness of the scene incident on the lens. The lens, in turn, determines the light collection and transmission capability and, hence, affects the exposure time required as well as the fidelity of the transmitted image. The motion of the spacecraft relative to the ground also affects the exposure time or, alternatively, determines the image motion compensation (IMC) requirements. The detector determines the light requirement and affects the fidelity of the retained image and the FOV (through the format size and the required ground size and resolution). Processing converts the latent detector image (film only) into a visible image. Factors such as the type of developer and developing time affect the contrast range in the developed image and, to some extent, the granularity of

the image. The readout step involves a systematic scanning of the film or TV target to convert the stored image into electrical signals. Scanning spot size and line spacing affect the fidelity of the readout scene. Data handling encompasses any onboard storage (such as magnetic tape) and conversion, formatting, or encoding functions required prior to actual transmission of the data to Earth. The transmitted signals are detected by the receiver and reconstituted by the ground reconstruction equipment.

To assess anticipated overall system performance, a suitable measure of performance must be defined and the effect of each of these system elements relative to this performance criterion determined. Unfortunately, there appears to be no single unambiguous measure of system performance. Perhaps the one in most common use is resolution but, considering the variety of possible interpretations, it leaves much to be desired. Clearly, a given imaging system has no one resolution capability. Rather, it is a variable depending on lighting, scene contrast, etc., and, even when all these factors are constant from one exposure to the next, film system resolution can only be accurately described in a statistical sense because of film and processing variations. In addition, resolution is a measure only of the high frequency cut-off of the system and it gives no idea of the overall shape of the frequency response characteristic. Consequently one system may have a higher resolution capability than another yet because of inferior low frequency response characteristics provide poorer relative performance in an imaging situation where low frequency response is important.

Despite these drawbacks, resolution still appears to be a useful tool provided that its limitations are understood. Prediction of the resolution capability of a system is difficult, however, and involves fairly complete understanding of the individual characteristics of each system element. Fortunately, the performance of some of these elements can be made as good as desired without significant penalties and, consequently has little or no effect on the overall performance of a properly designed system. These elements include processing,

readout (TV only because readout degradation is included in the sensor performance), data handling, transmitting, receiving, and ground reconstruction functions. Indeed, some of these components, notably ground reconstruction, are generally designed to improve the imagery by contrast enhancement techniques or other computer type manipulation. Therefore, it is reasonable to disregard these elements in any preliminary assessment of system performance.

The inconsistencies extant in defining TV and photo system resolution also cause confusion. Most of this difficulty stems from the fact that the TV image is read out using a line scan while a typical hard copy photograph has no analogous line structure. Yet, photographic resolution has traditionally been quoted in terms of line pairs/mm. However, photographic line pairs are visually determined from a photograph of a test chart consisting of various size patterns of lines and spaces. Therefore, such a definition of photographic resolution is a direct measure of the capability of the photographic system to record detail. Today, photographic line pairs are construed to mean line-space pairs, and, consequently, this measure of performance corresponds approximately to spatial frequency response in lines/mm or cycles/mm as used on standard modulation transfer function (MTF) plots which will be discussed later.

TV lines have no similar direct connection to actual system performance. The number of active raster lines represent only the upper limit of resolution capability and, even in situations where this limit is achieved, TV lines still overstate the resolution capability as compared to a photo system by a factor of two since a minimum of two raster lines are required to reproduce a line-space pair on a real target or, alternatively, to just detect a contrast change in the imaged area. In practice, realized TV resolution, after taking into account the other system elements, is normally considerably less than this ultimate capability.

In addition to the degradation in TV (or photo system) performance produced by the lens, contrast, etc., scanning also produces degradation if the number of active scan lines closely approximates the actual system

resolution in lines. In this event, the Kell factor, (Ref. 1) which expresses the ratio between the number of resolvable black and white lines and the number of scan lines, must be taken into account. Generally, the Kell factor is taken as 0.7 although this is clearly an oversimplification since the actual system bandwidth must be considered to adequately define the Kell factor for that system. However, in cases where the number of active scan lines exceeds the number of resolution lines by more than 30-50%, the Kell factor is generally not important.

It should not be assumed that the Kell factor applies only to TV systems. In the case of photo systems using a flying spot or other type of raster scan, the same considerations are appropriate. Typically, however, the number of active scan lines in these cases exceeds the system resolution and, consequently, the effect is normally minimal.

SYSTEM ANALYSIS

The MTF is a measure of contrast transfer by an imaging system component or the entire system. It is defined as the ratio of the output to the input modulation intensity of a sinusoidal pattern at a given spatial frequency. Thus, a value of 1.0 corresponds to a faithful reproduction of the input pattern and a value of zero represents no signal transfer. A complete system, or each of the components of a system, has a unique MTF. The system modulation transfer is given by the product of the individual component transfers. Thus, for a TV system

$$T_o = T_c T_v T_a T_m T_s$$

where

T_o = overall system MTF
 T_c = contrast
 T_v = sensor (includes readout for TV)
 T_a = lens
 T_m = image motion
 T_s = other elements

To visually detect a contrast change in some part of an imaged scene, the overall system transfer, T_o , at the pertinent spatial frequency must equal or exceed the visibility threshold, taken here as 0.04. This figure assumes a signal-to-noise ratio high enough so that performance is contrast limited. Since a spaceborne imaging system generally must record a wide variety of scenes, a conservative contrast value should be used to insure the required minimum system performance level under worst case conditions. Typically, contrasts in the range of 1.3:1 to 2:1 are observed from high altitudes. Consequently, a value of 1.3:1 is used here. Then, the contrast, T_c , is:

$$T_c = \frac{1.3-1}{1.3+1} = 0.13$$

Consequently, assuming the product of the transfer functions of the other elements, lumped into T_s , equals one (since these elements can generally be made as good as desired), the product

$$T_v T_a T_m \geq 0.31$$

The value T_v is determined in each case by the image plane resolution required to satisfy the measurement task. Therefore, the transfer function associated with the lens and the image motion must be given by:

$$T_a T_m \geq \frac{0.31}{T_v} \quad (1)$$

or the required image plane resolution cannot be realized.

The various combinations of lens and image motion transfer functions that satisfy Eq. (1) for various values of T_v are shown in Figure 2.

For a film system, the same considerations apply except that the performance of the readout system and the type of film used must be taken into account as discussed later.

In preliminary mission studies, a useful estimate of the component requirements can be obtained by assuming that each component of the system, except for T_s which is assumed equal to one, contributes equally

to the system contrast transfer loss. On this basis, a TV system consists of three components, i.e., the lens, sensor and IMC. Thus, each component of a TV system must have a modulation transfer of at least 0.68 at the spatial frequency required by ground resolution considerations to provide an overall system transfer, T_o , equal to 0.04 for a minimum contrast, T_c , of 0.13. Obviously, equal allocation of loss is not mandatory but if any one element is degraded significantly below the levels indicated, the requirements on the remaining system elements tend to become completely unrealistic except for low resolution systems.

The essential point is that the low contrast available at the spacecraft places severe requirements on the performance of the remaining system components. The impact of these requirements will be discussed in the following sections.

COMPONENT ANALYSIS

The Lens

Even very high quality lenses, corrected so that their performance is limited only by diffraction effects, have an important impact on overall system performance. Lens aberrations, present in typical practical lenses, further degrade overall performance. However, as computer aided design and lens grinding techniques become more commonplace, it is probable that truly diffraction limited lenses will become the norm for demanding applications.

The performance limitation in a diffraction limited lens is a consequence of the diffraction pattern produced by the aperture. Because of this phenomenon, a point source of light is imaged not as a point but as a bright central disk surrounded by alternate dark and light rings of rapidly diminishing intensity. Thus, ultimate resolution in a diffraction limited lens is determined primarily by the size of the central disk. The disk diameter is

$$d = 1.22 \lambda / D$$

where λ is the wavelength and D is the effective aperture of the lens.

In Figure 3, the transfer function T_a for a diffraction limited lens is given in terms of Ω , the ratio of the diameter of the actual lens aperture to the diffraction limited aperture. This generalized curve is useful for determining how much larger than the diffraction limited size a lens must be to achieve a desired level of modulation transfer at the spatial frequency required. Figure 4 shows the f stop required as a function of spatial frequency to achieve various levels of modulation transfer. (In some situations, the light gathering requirement may dominate; these curves consider only the resolution requirement.) Figure 5 shows spatial frequency versus ground resolution for various photographic scales where the scale, S , is defined as the ratio of altitude to focal length. Ground resolution here implies only the ability to detect a contrast change over that distance. The number of resolution elements required per object or feature for recognition or identification depends on the shape, texture and size of the feature and the lighting conditions under which the imagery is obtained.

Image Motion

Relative linear or vibrational motion between the light rays originating at the scene and the recording medium during exposure result in increased resolution element size and thus contribute to overall image degradation. In addition, random variations produced by atmospheric conditions such as turbulence and temperature fluctuations produce similar effects. Since vibrational problems are minimal or non-existent for most unmanned spacecraft except during or immediately after a maneuver, the main problems are linear motion and atmospheric effects. Since the latter are not within design control, a priori estimates can only be made on the basis of either typical or worst case conditions.

Average turbulence for daytime reconnaissance of the Earth is believed to be about two to four seconds of arc with extremes under poor seeing conditions ranging to 40 sec of arc (Refs 2,3,4). The RMS displacement as a function of mean angular displacement for two turbulent layer altitudes is shown in Figure 6, clearly a very simplified approach. However, considering typical spacecraft altitudes,

the fact that turbulence is probably distributed through the atmosphere rather than in a layer would have small effect. In this paper, degradation caused by atmospheric turbulence has been included in the value assumed for contrast, T_c .

The transfer function for linear image motion caused either by image motion compensation errors or attitude control rates or both is shown in Figure 7 in terms of the ratio of image displacement to resolution element size. Resolution element size as a function of spatial frequency is shown in Figure 8. Tolerable image motion during exposure as a function of spatial frequency for 68% and 75% modulation transfer are shown in Figure 9. The longest tolerable shutter speed can be obtained for any imaging situation by projecting the tolerable image plane motion to the ground surface using the photographic scale (ratio of spacecraft altitude to lens focal length) and dividing by the net spacecraft ground velocity. Thus, the longest shutter speed is given by

$$t = \frac{S \times I}{V} \times 10^{-9} \quad (2)$$

where

S = photographic scale (See figure 5.)

I = tolerable image motion (μm)

V = net spacecraft ground velocity (km/sec)

Scene Luminance

The shutter speed determined above must be compared with the shutter speed required by the available light. For television systems, the exposure time is

$$t_e \geq \frac{4 s (f \text{ no.})^2 F F}{n B}$$

where

s the tube sensitivity is given in Table 1

$f \text{ no.}$ is the lens stop

$F F$ is the filter factor

n is the optical system transmission factor (taken as 0.9 for short focal length lenses)

B is scene luminance from altitude (foot-lamberts)

A similar expression applies for film systems where the exposure time is

$$t_e \geq \frac{0.6 (f \text{ no.})^2 F F}{n B (AEI)}$$

and

AEI, the aerial exposure index, is given in Table 2

If the exposure determined from these expressions should be longer than that determined in (2) above, then either image motion compensation must be provided or a larger lens aperture must be used.

Table 1
Electro-Optical Sensor Sensitivity

<u>Sensor</u>	<u>s (foot candle seconds)</u>
Vidicon	3×10^{-3}
Plumbicon	2×10^{-3}
Return Beam Vidicon	1×10^{-3}
Secondary Electron Conduction Vidicon	5×10^{-5}
Image Orthicon	2×10^{-6}

Table 2
Aerial Exposure Indices of Some Films

<u>Film No.</u>	<u>Aerial Exposure Index</u>
S0-243	1.6
3404	1.6
S0-230	6
S0-206	6
S0-226	6
3400	20
S0-136	20
3401	64

The Detector

The image formed by the optical system must be stored or converted directly to a signal that can be used to reconstitute the image. Sensors commonly used for this purpose include light sensitive and electro-sensitive surfaces as exemplified by photographic film and vidicons, respectively. While in many ways the two approaches are analogous, major differences do exist. The most significant, perhaps, is the fact that the film must first be processed and then read out by an electro-optical scanner for transmission to Earth (for some applications direct return of the unprocessed film is an alternative, albeit a costly one) while the TV system provides an electric charge 'image' that is directly read out by an electron beam without intermediate processing. However, at the present state of the art, the information storage capacity of film far exceeds that of the best TV tubes. Consequently, system selection depends primarily on resolution-coverage considerations.

The resolution capability of film is ultimately determined by signal-to-noise ratio considerations. Selwyn (Ref. 5) has developed a method relating signal and noise for idealized sine wave targets* or, with less accuracy, square wave bar targets. The resulting visual resolution limit in lines per millimeter is

$$R = \frac{\gamma C \tau(R)}{KG} \quad (3)$$

where

γ is the film contrast

C is the target contrast (at the lens)

$\tau(R)$ is the system transfer function

K is the minimum detectable signal to noise ratio

and $G = \sigma D$

where G is the granularity constant

σ is the RMS noise fluctuation

and D is the scanning aperture diameter (mm)

* Targets in which contrast varies sinusoidally across the scene. Resolution is defined as the ability to resolve adjacent peak amplitudes of contrast and thus is given by the resolvable wave length of such a sinusoidal distribution.

When G becomes small, the resolution capability of the system is no longer noise limited and the contrast threshold of the eye, about 0.04, becomes the limiting effect. When this operating regime is dominant, equation (3) becomes

$$\gamma C \tau(R) = 0.04$$

However, for most films performance is generally noise limited when imaging low contrast scenes. The performance of some standard aerial films in terms of modulation thresholds (Ref. 6) is shown in Figure 10. These thresholds represent the impressed modulation, or overall system modulation transfer, required of the film to permit resolution at a given spatial frequency. The film MTF and gamma ($\gamma = 2$) are included in these curves.

Since impressed modulation is just the product of the image modulation and the modulation transfers for each component of the system preceding the film (the effect of the scanning system* is also included for convenience although strictly speaking it is located after the film in the system), the modulation transfer required of each component is

$$T = \left(\frac{\text{Impressed Modulation}}{\text{Image Modulation}} \right)^{1/3}$$

The modulation transfer required of each system element as a function of spatial frequency for some aerial films is shown in Figure 11. These curves assume that three system elements, i.e. the lens, image motion compensation, and the scanner, are involved in addition to the film.

Typical MTF data for TV tubes is given in Figure 14. At the present state of the art, TV tube format sizes are limited to a maximum of about 2" x 2". The resolution capability of some of these tubes at 68% modulation transfer is given in Table 3. These figures represent the system resolving power under the operating

* The performance of current flying spot scanners (Ref. 7) is shown in Figure 12. The scanner spot size for a modulation transfer of 0.75 as a function of spatial frequency can be specified as shown in Figure 13. Of course, the same considerations apply to the electron beam in electro-optical sensor readout but any signal degradation from this source is already accounted for in the tube MTF.

conditions assumed. Here, however, readout is included but data handling, transmission, and ground reconstruction are not.

Table 3
Resolution Capabilities (L/mm) of Some Electro-
Optical Sensors at 68% Modulation Transfer

WL-32000	3
WX-5419 B	6
WL-7290	11
4.5" RBV	32

Other System Elements

The remaining system elements include data handling, transmission, reception, and ground reconstruction. Data handling, transmission, and reception elements can normally be designed so that their MTF's are close to unity at the maximum spatial frequency of interest without incurring significant penalties. Clearly, for planetary missions practical limitations on transmitter power limit the transmitted data rate and, consequently the resolution and coverage that can reasonably be achieved; but, since the tolerable error probability will undoubtedly be kept low, e.g., one error per thousand bits, an MTF close to unity is reasonable.

Ground reconstruction systems are generally designed to improve the available contrast and sharpness and to decrease the noise level. However, meaningful generalizations about ground reconstruction systems are difficult and it is probably best to assume that acceptable imagery, according to the criteria discussed earlier, should be available before improvement by ground reconstruction techniques.

EXAMPLE

To illustrate the use of the method described above, a film imaging system application will be analyzed. Assume that the required resolution is 20 meters per line pair and the total field of view required at the surface is 100 km x 100 km. The minimum contrast anticipated at the lens is 1.3 to 1 and the scene luminance at altitude is 800 foot-lamberts.

Under low contrast conditions, film systems can conveniently provide a spatial frequency response in the range of 10 to 100 lines per millimeter (see Figure 11). Referring now to Figure 5, a photographic scale of about 10^6 will result in an acceptable image plane spatial frequency of 50 lines per mm for a ground resolution of 20 m. Since the photographic scale is equal to the ratio of the ground size to the format dimension, the film format size required is given by

$$d = \frac{G}{S} \times 10^6 \quad (\text{mm})$$

where G is the ground size in km and S is the photographic scale. For a ground size of 100 km and a photographic scale of 10^6 , the format dimension is equal to 100 mm. Since 5" film has a format size of 114 mm, it represents a good choice. Referring again to Figure 11, two film types, S0-206 and 3404, can meet the 50 line per mm image plane requirement at a contrast of 1.3 to 1 without requiring unreasonable modulation transfer from the outer system elements. For this example, we will select S0-206 which requires a transfer of about 0.75 for each of the other system elements.

The lens required for this system is readily determined from Figure 4. At 50 lines per millimeter and 75 percent transfer, a lens stop a little smaller than f/6 is tolerable. The closest satisfactory standard stop is f/6.3.

The flying spot scanner spot size required for a transfer of 75 percent at this spatial frequency is given in Figure 13. For this level of modulation transfer the spot size should not exceed about 10 microns.

The tolerable image plane motion for the required performance level is given in Figure 9. Image plane movement during exposure with no image motion compensation should not exceed 9 micrometers. For a nominal Earth orbital velocity of 7.8 km per second, the longest shutter speed tolerable with no IMC is given by

$$t_e \leq \frac{S \times I}{V} \times 10^{-9}$$

where S is the photographic scale, I is the image plane motion in micrometers and V is spacecraft velocity in km per second. For the values of this example, the exposure time is

$$t_e \leq \frac{10^6 \times 9}{7.8} \times 10^{-9} = 1.15 \times 10^{-3} \text{ sec}$$

Since the maximum exposure time is somewhat more than 1/1000 of a second, a standard shutter speed of 1/1000 would be used.

Only one step in the systems specification remains -- the focal ratio required to meet the resolution requirements must now be checked against the focal ratio required by lighting considerations. The lens stop required for sufficient light is

$$f \text{ no} \geq \left[\frac{n B (AEI) t_e}{0.6 FF} \right]^{1/2}$$

where n is the optical system transmission factor (taken as 0.9 for short focal length lenses), B is scene luminance from altitude (foot-lamberts), AEI is the aerial exposure index of the film (see Table II), and FF is the filter factor. Assuming that no filter is used, the minimum f stop required here is

$$f \text{ no} \geq \left[\frac{0.9 (1000) 6 (10^{-3})}{0.6} \right]^{1/2} = 3$$

Since the f stop required must be greater than f/3, a standard aperture of f/2.8 would be selected. Since the aperture required by lighting conditions is greater than the aperture required by the

resolution considerations in this case, the lighting requirements would be dominant and an $f/2.8$ lens would be chosen. Clearly an aperture of this size will provide more than adequate performance to meet the 75 percent response at 50 lines per mm.

The shutter speed requirement could be easily reduced by an order of magnitude with image motion compensation which would result in a focal ratio requirement of about $f/9$ rather than the value of $f/3$ previously mentioned. Then the lens aperture requirement determined by resolution requirements ($f/6.3$) would be dominant and that value would be used with a somewhat higher shutter speed.

The approach outlined in this example was chosen because of the character of the input data used. Depending on the exact nature of the input data, other approaches may be more desirable. The data contained in this report is intended to fit many different situations and the exact procedure to be used in each case should be tailored to fit the requirements.

CONCLUDING REMARKS

In assessing the performance capabilities of optical imaging systems for space applications, it is generally of first importance to determine whether or not the resolution/coverage requirements for a given experiment can be met. Even for very preliminary analyses, coarse determinations based only on the film or electro-optical sensor performance can be exceedingly misleading. Consequently, some technique for realistically approximating the performance of the overall system is required.

The approach described here makes it possible to quickly and systematically estimate overall system performance and, thereby, to assess the feasibility of meeting a given imaging requirement.

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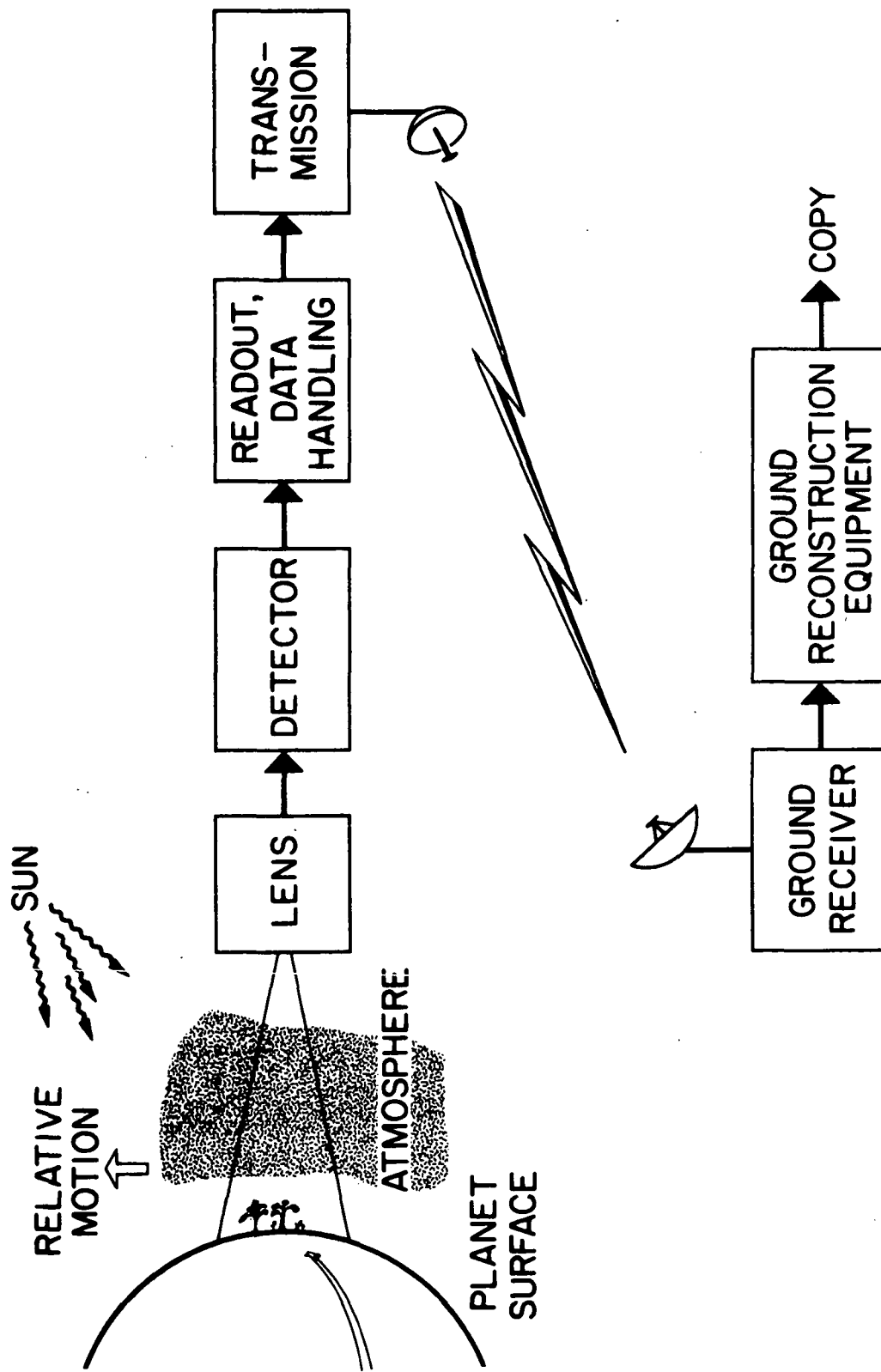


Figure 1 Imaging System Block Diagram

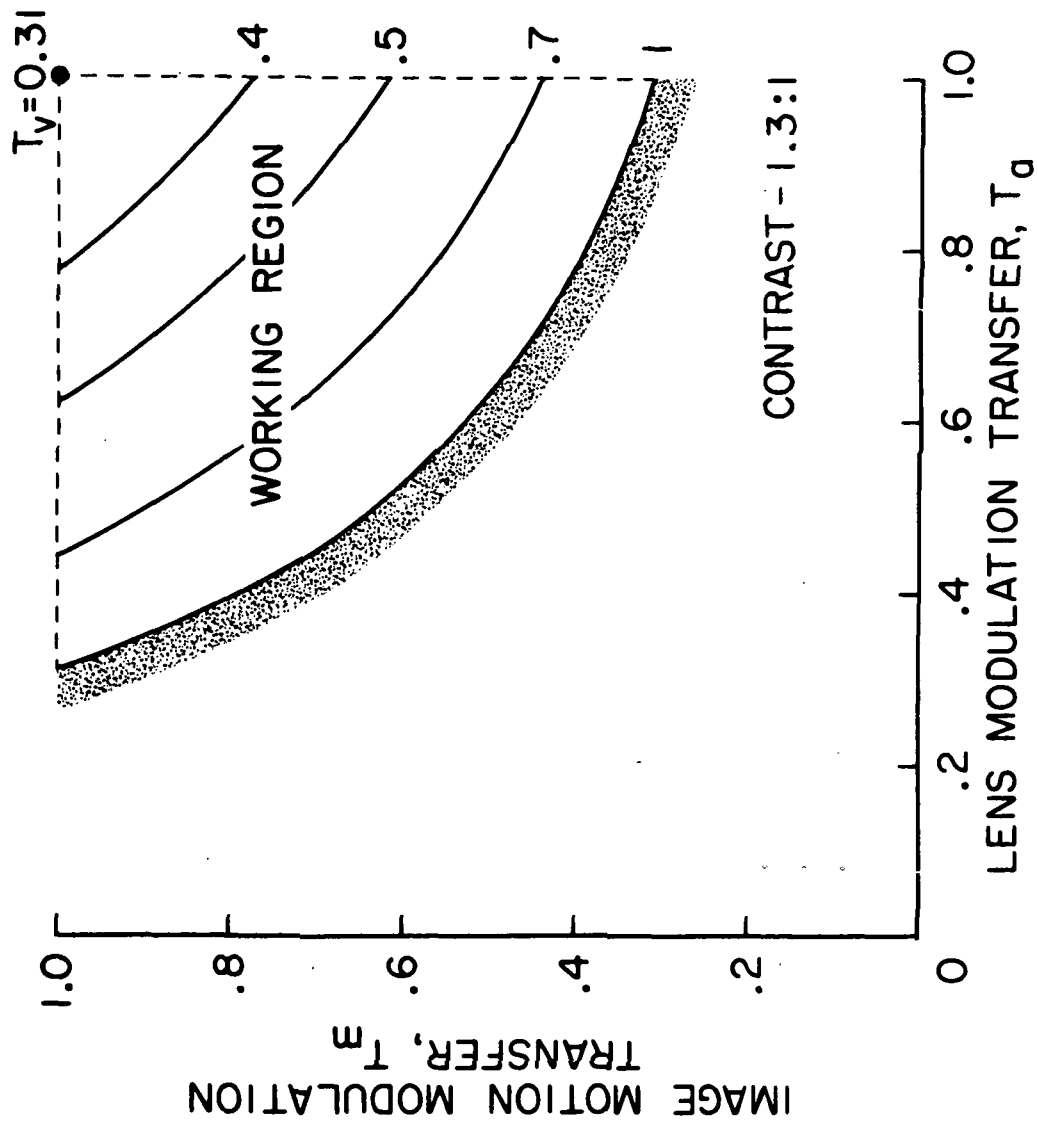


Figure 2 Lens and Image Motion Transfer Functions

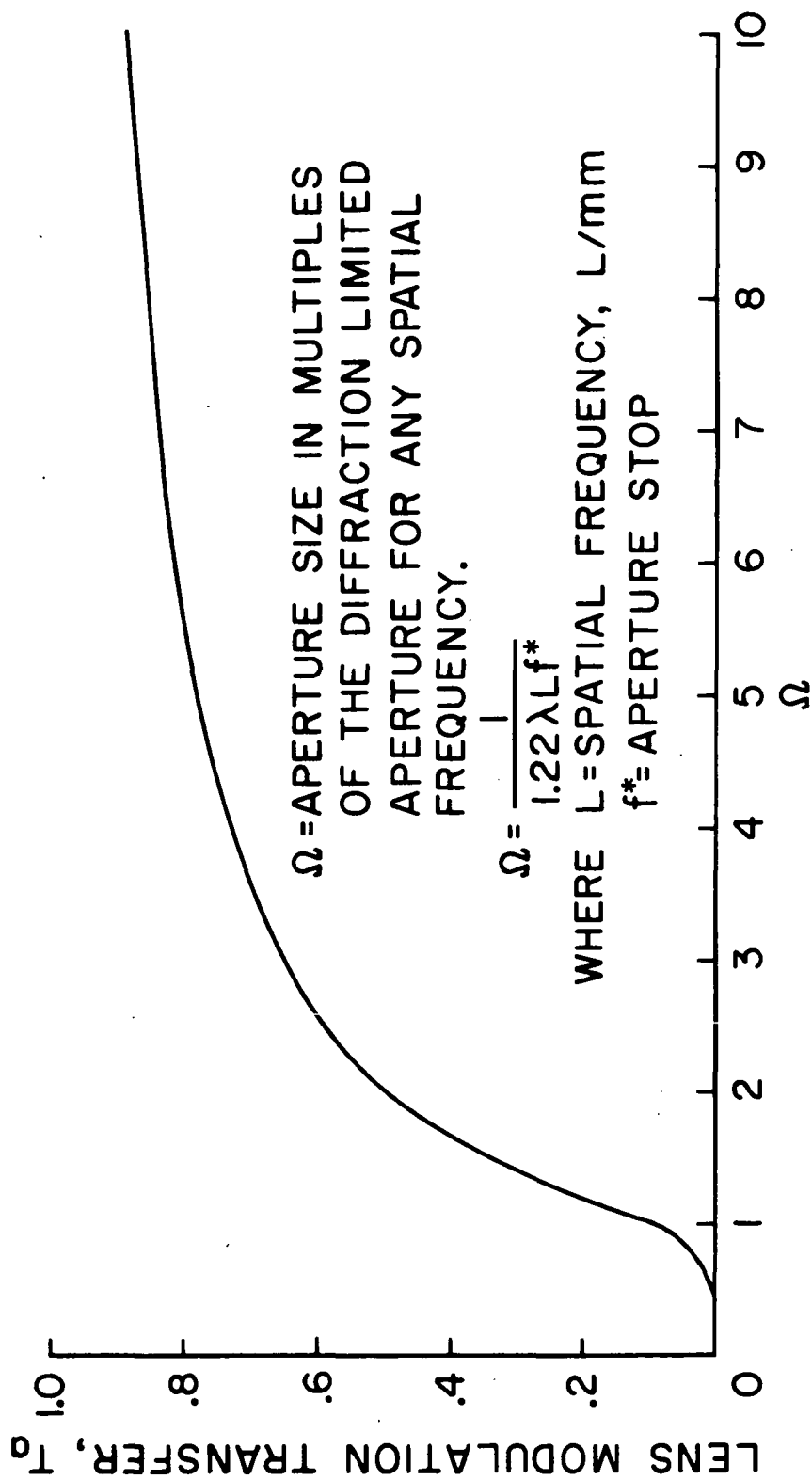


Figure 3 Lens Modulation Transfer with Aperture Size

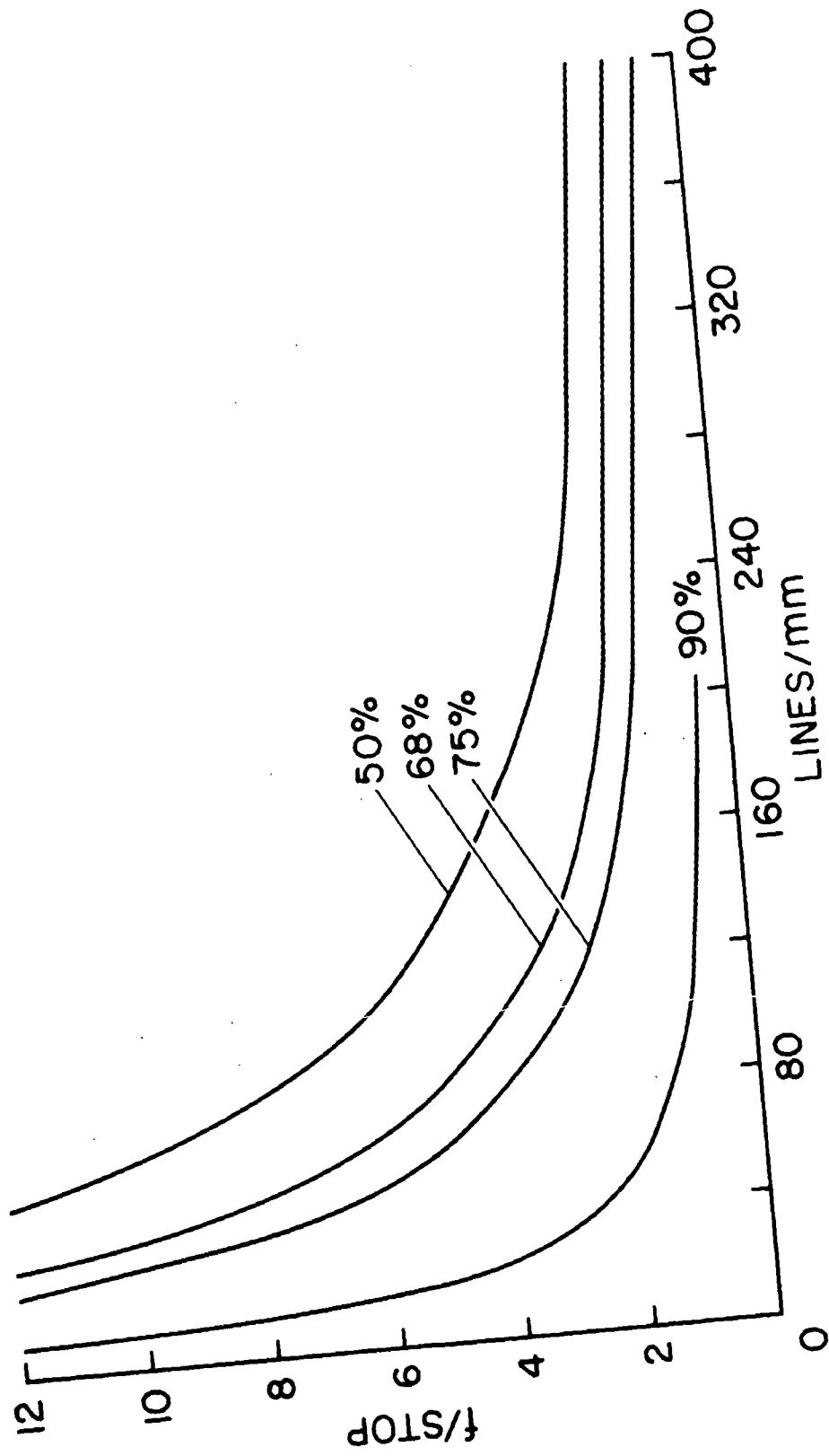


Figure 4 Lens Stop for Fixed Modulation Transfer

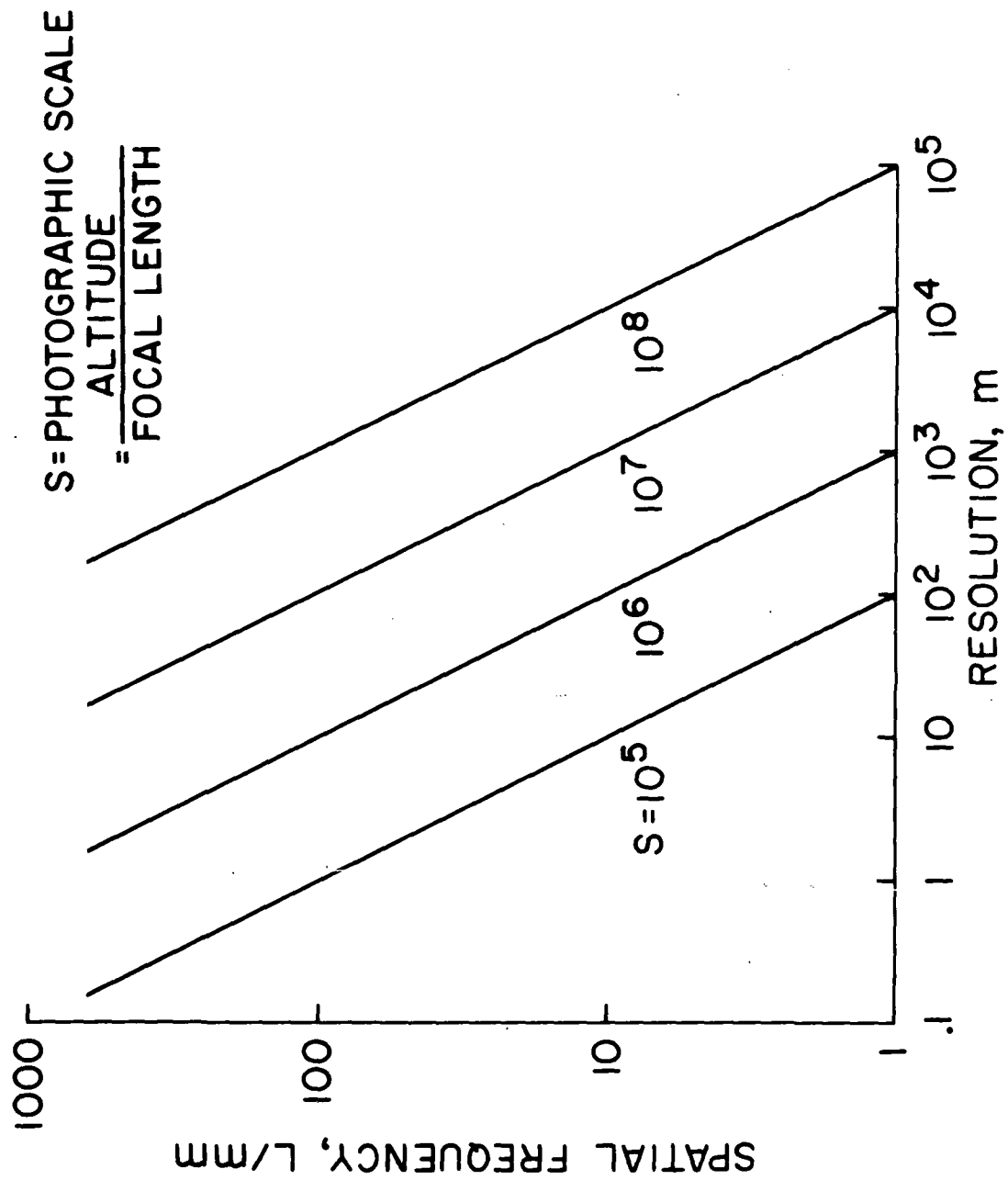


Figure 5 Ground Resolution Capability

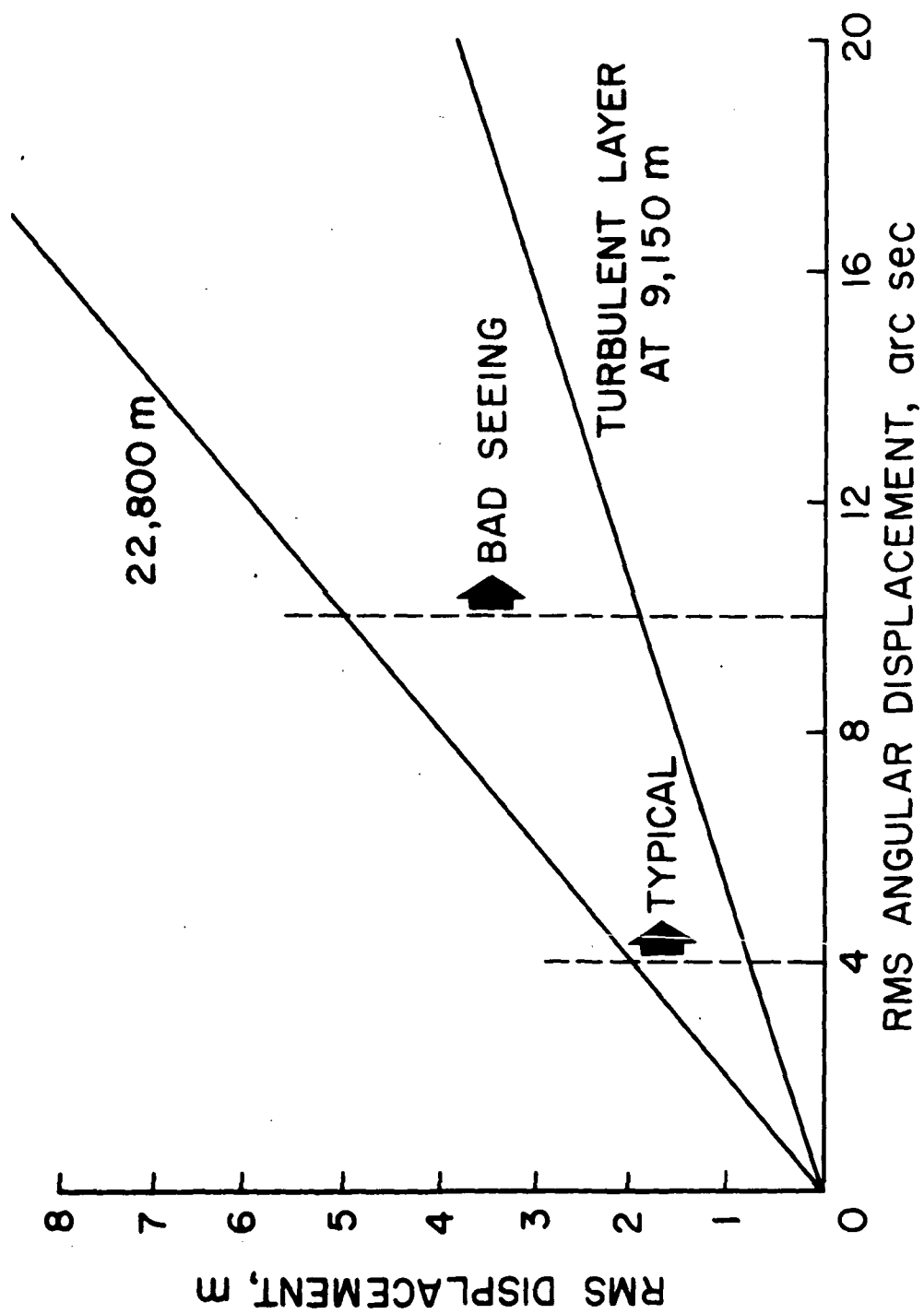


Figure 6 Turbulence Effects

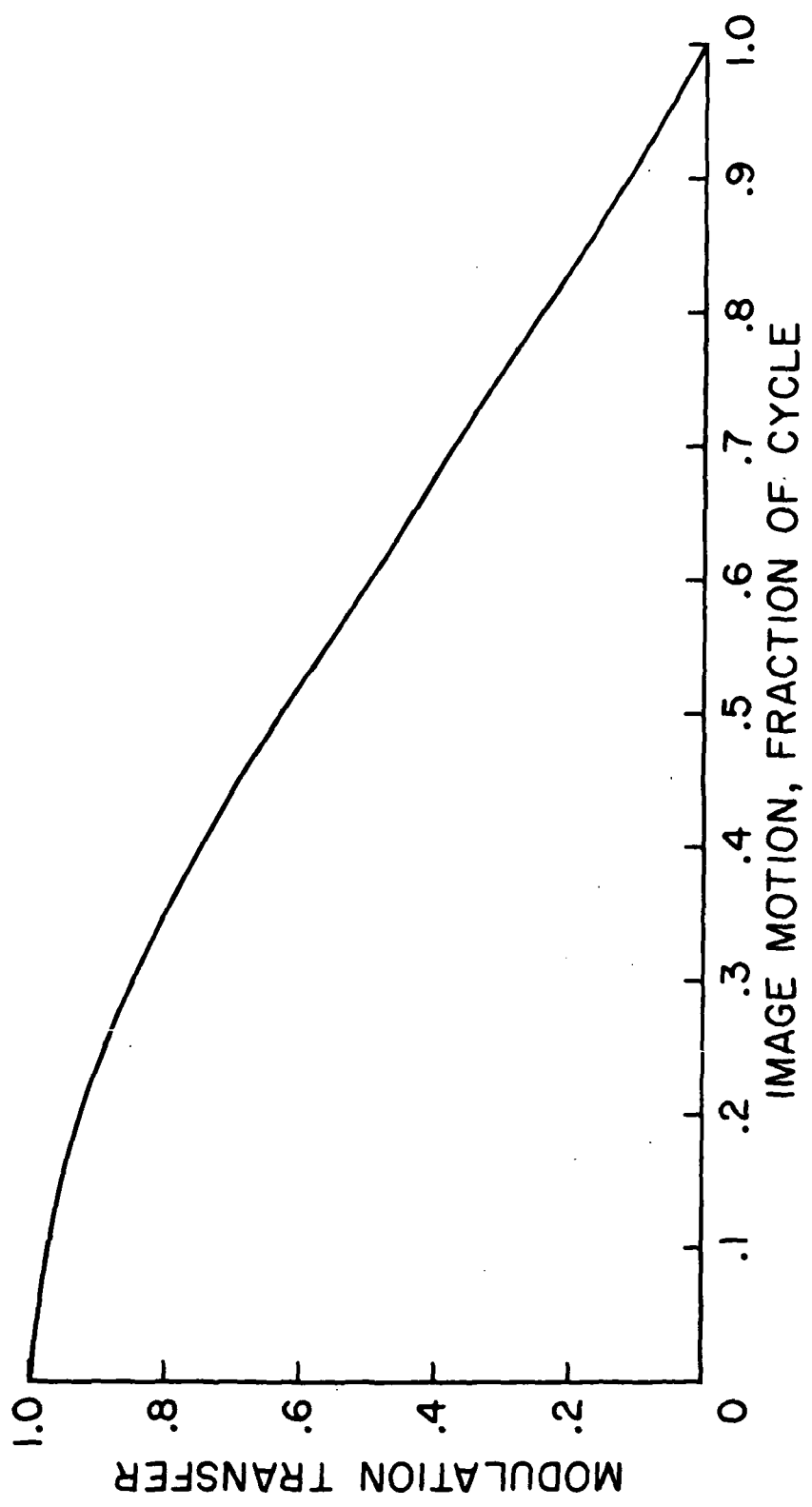


Figure 7 Image Motion Transfer Function

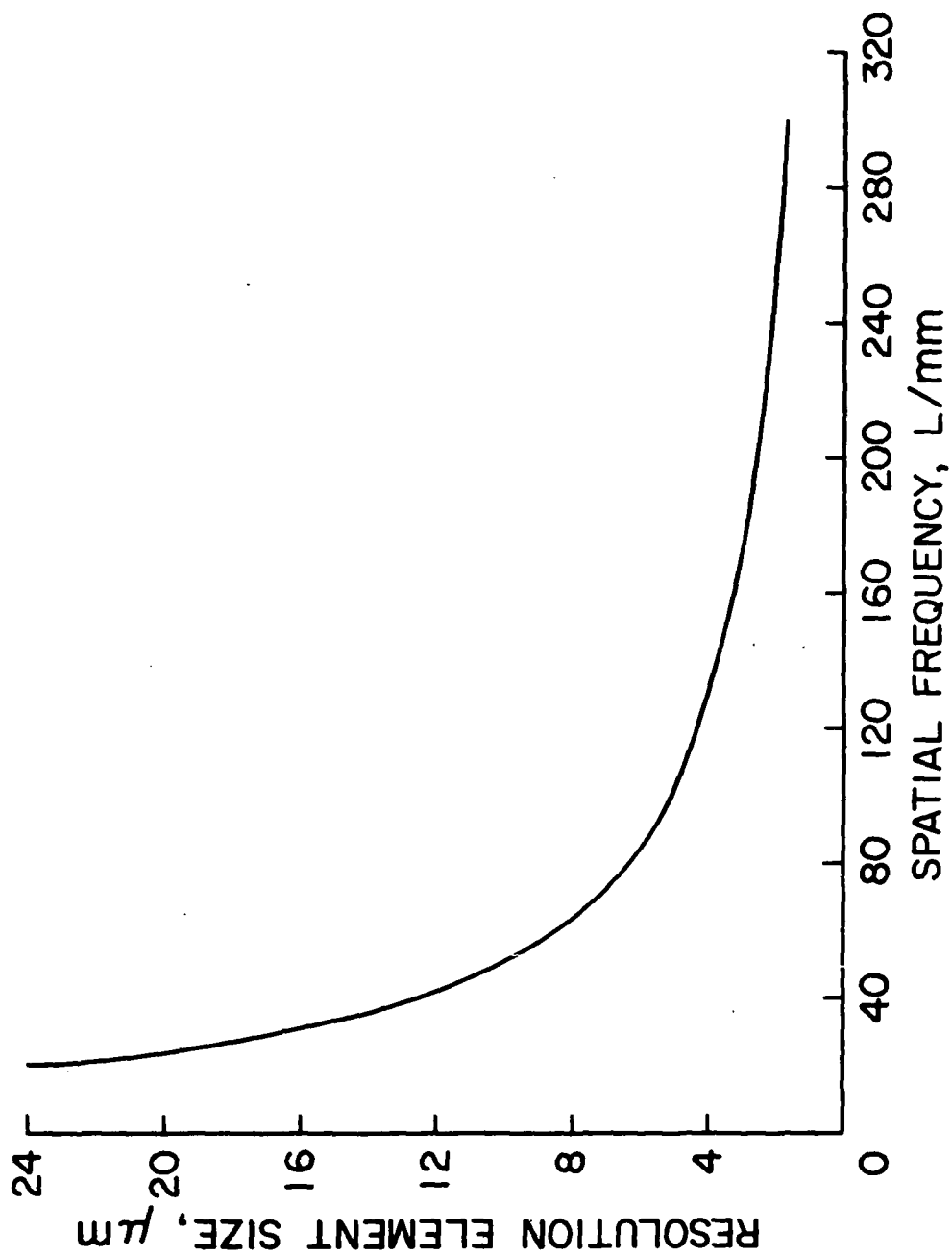


Figure 8 Image Plane Resolution Element Size

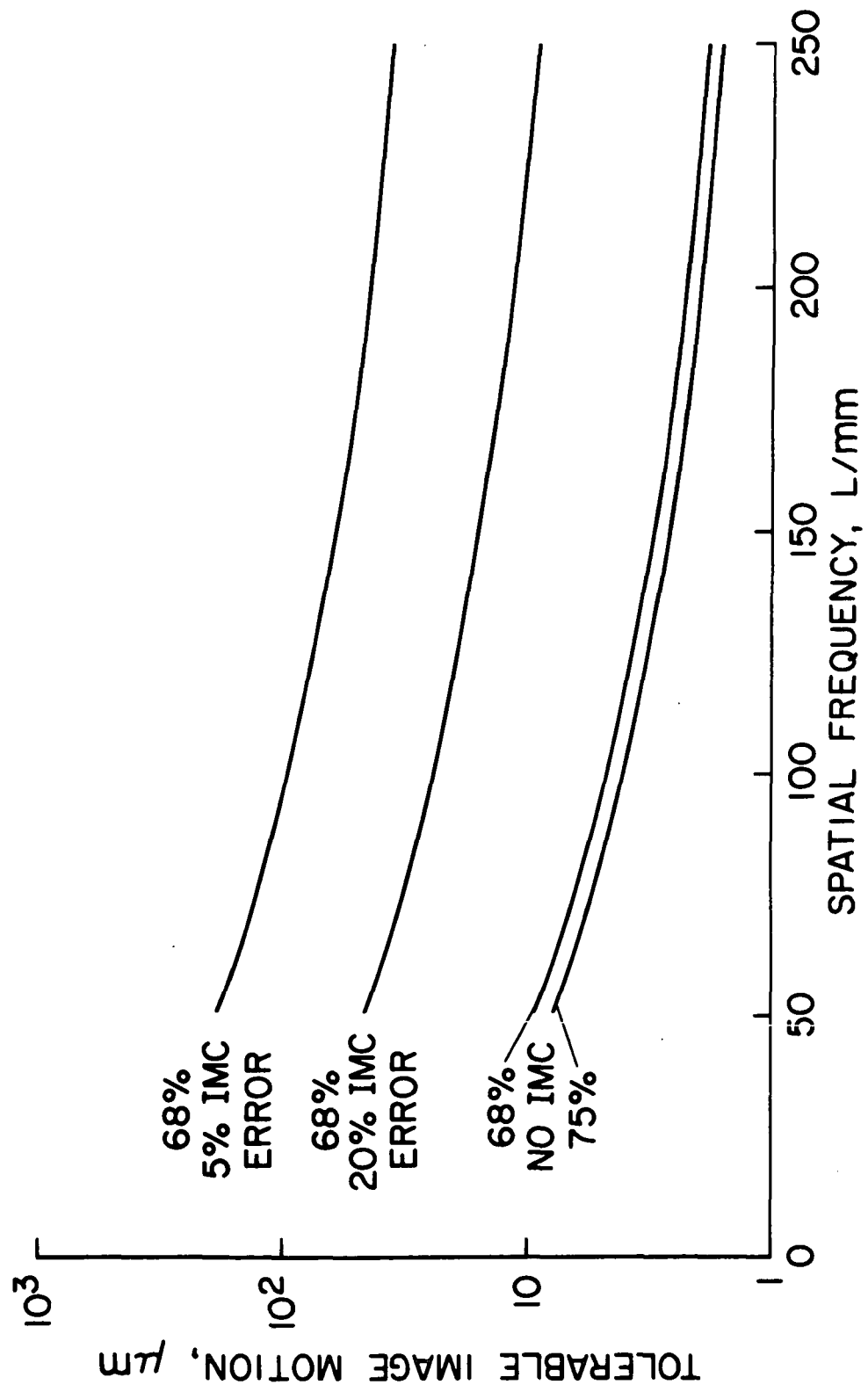


Figure 9 Tolerable Image Motion for Fixed Modulation Transfer

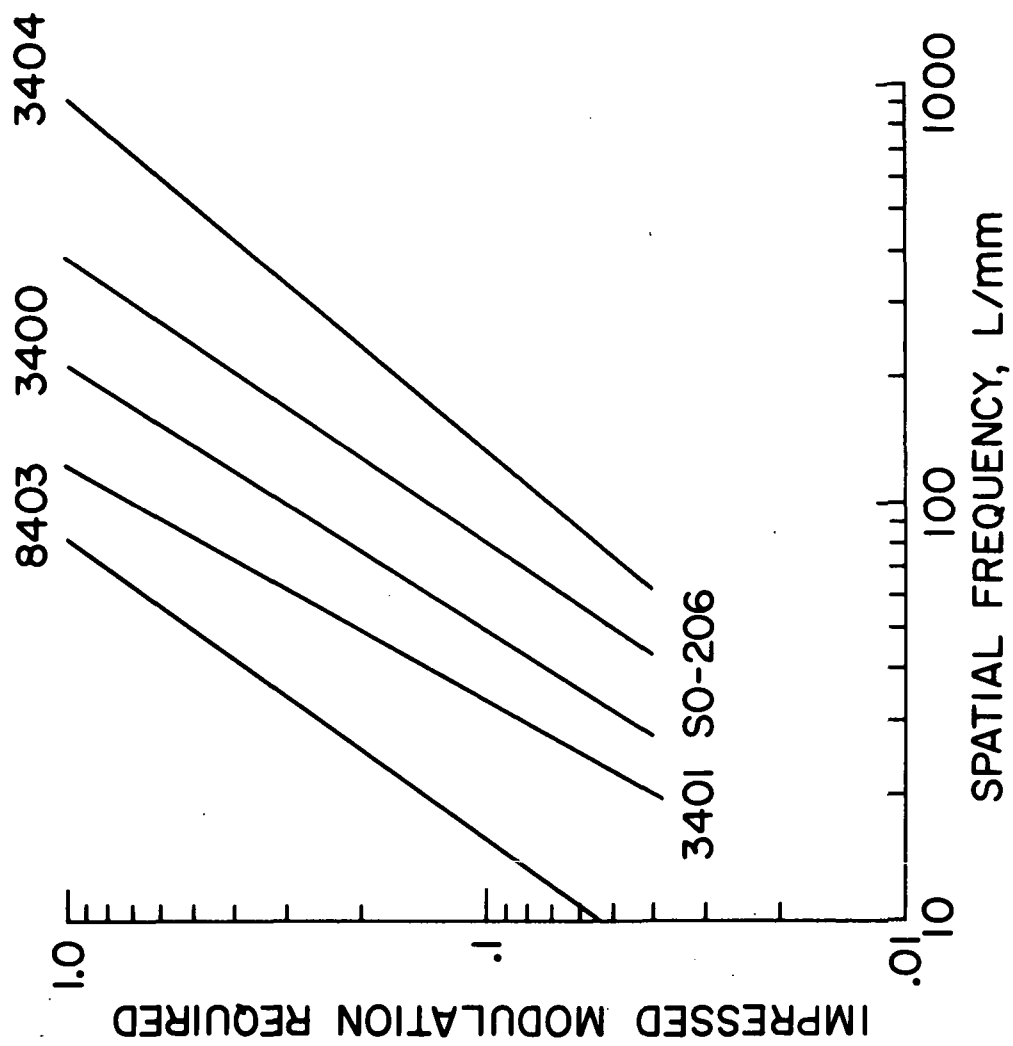


Figure 10 Film Modulation Thresholds

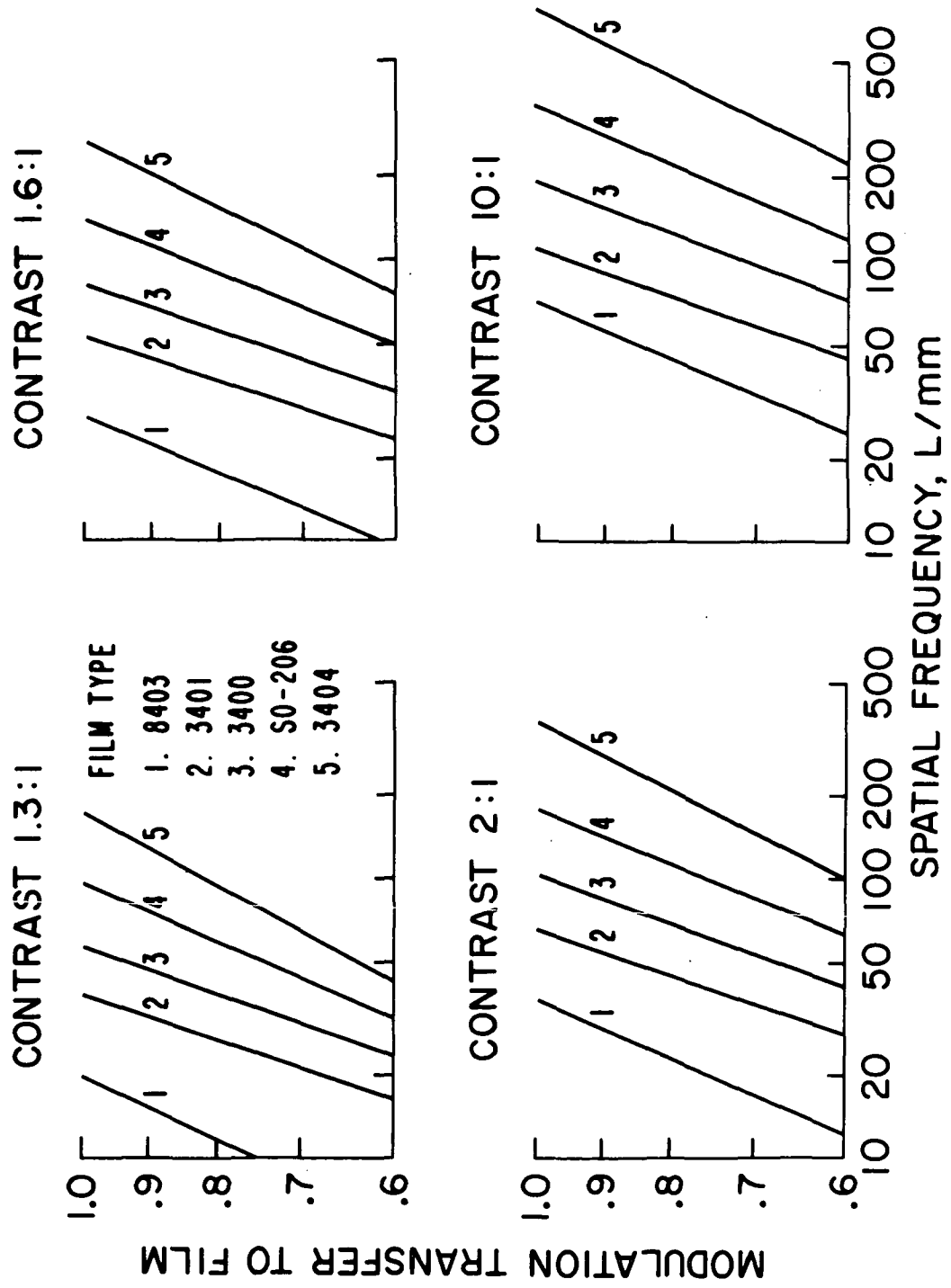


Figure 11 Required Modulation at Film

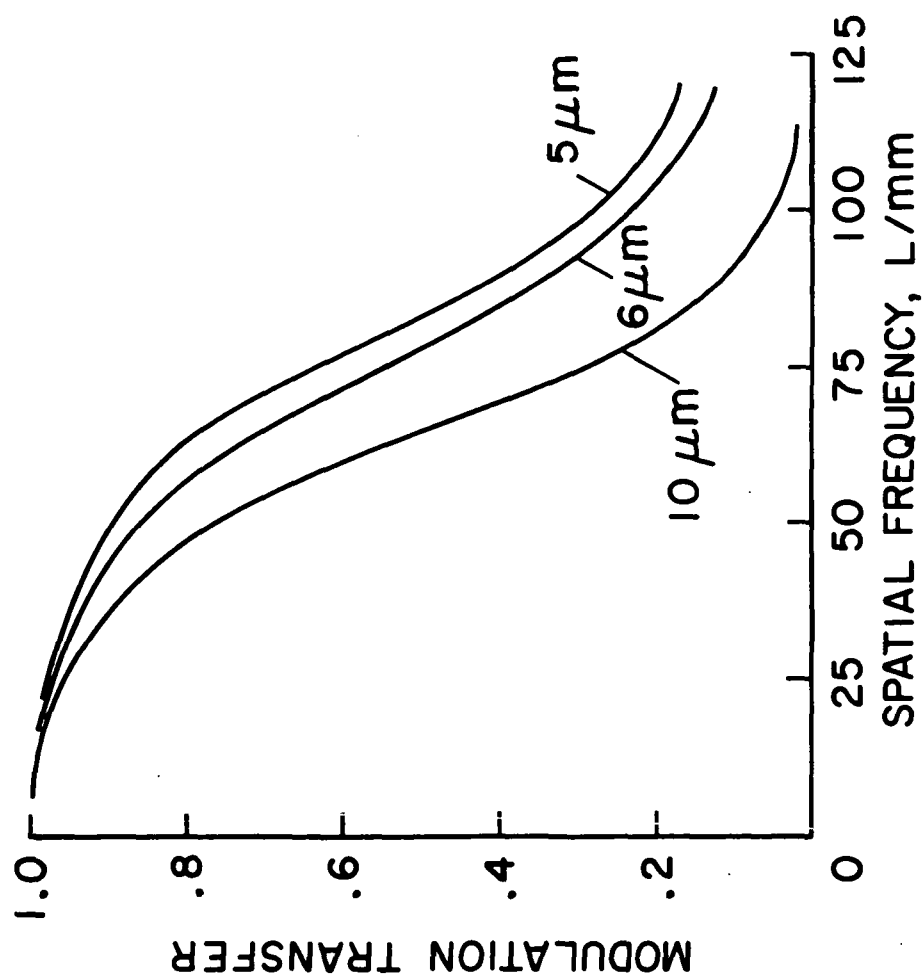


Figure 12 Flying Spot Scanner Modulation Transfer

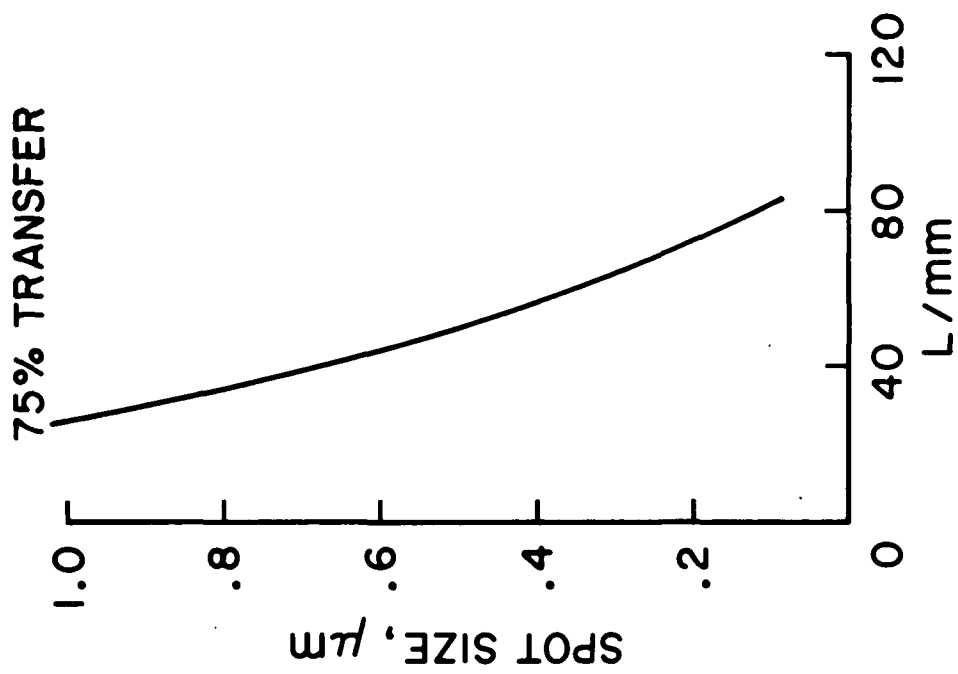


Figure 13 Scanner Spot Size Requirements

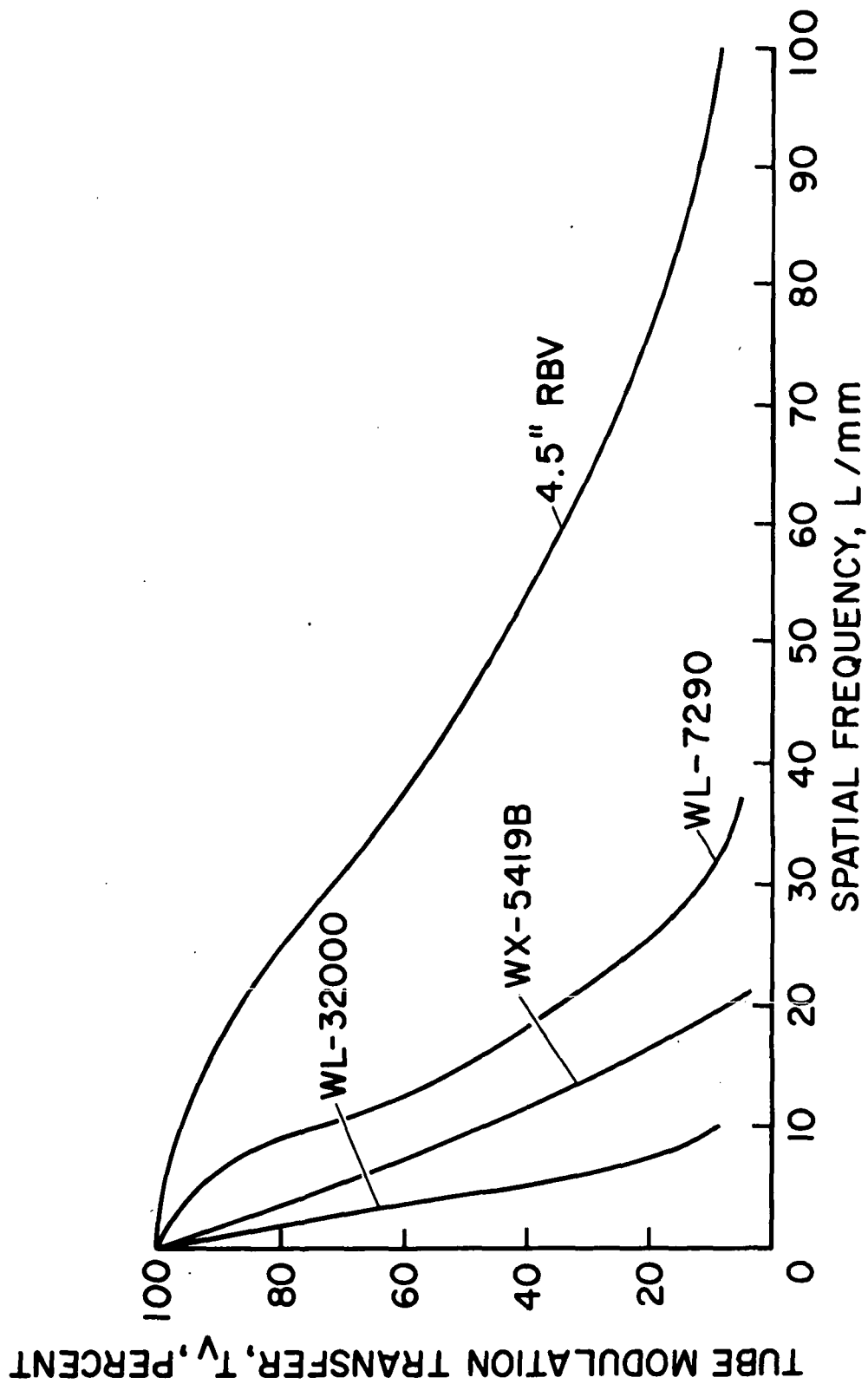


Figure 14 MTF Data for Some Electro-Optical Sensors